Behavioral Convergence Properties of Cournot and Bertrand Markets: An Experimental Analysis

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Abstract

This paper reports an experiment that examines the relative convergence properties of differentiated-product Cournot and Bertrand oligopolies. Overall, Bertrand markets tend to converge to Nash equilibrium predictions more quickly and more completely than Cournot markets. Further, when products are close substitutes Bertrand markets respond more quickly to an announced nominal shock. As products become weaker substitutes, however, an increased tendency for tacit collusion degrades convergence in Bertrand markets. This effect is particularly pronounced following a nominal shock. Our results suggest that in an oligopoly context variations in decision error costs dominate a 'Strategic Substitutes Effect' isolated in previous experimental research.

Keywords: Experiments, Strategic Substitutes and Strategic Complements, Bertrand and Cournot Markets

JEL codes C9, D4 and L4

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I. Introduction

For decades, the convergence properties of Bertrand and Cournot oligopolies have been themes of continuing interest among economists. In Bertrand markets price choices are *strategic complements*, meaning that high expected rival prices induce high optimal seller price responses. This incentive for sellers to mimic rivals' actions causes Bertrand markets to drift, often very slowly, toward equilibrium predictions, as has been observed extensively in the experimental literature (e.g., Plott, 1989, Holt, 1995). On the other hand, games where actions are strategic complements uniformly satisfy Milgrom and Roberts' (1991) Adaptive Learning Criterion ('Adaptive Learning') and for this reason actions converge to the set of underlying Nash equilibrium under a wide variety of learning dynamics including Bayesian learning, fictitious play and Cournot best responses, among others.

The convergence properties of Cournot markets differ distinctly. The quantity choices in Cournot markets are *strategic substitutes,* meaning that high expected rival quantities imply a low optimal quantity choice for a seller. The incentive for Cournot sellers to respond to an expected deviation from the equilibrium by rivals with an own deviation in the opposite direction dampens the 'drift' characteristic of Bertrand markets, and thus may hasten convergence. On the other hand, however, Cournot games with more than two players do not uniformly satisfy Adaptive Learning. In such contexts, Adaptive Learning is satisfied only when a 'contraction condition' holds, namely that the absolute value of the slope of each sellers' quasi-reaction function is less than one (Vives, 1999). Importantly, this contraction condition is violated in a variety of policy-relevant contexts, including the standard textbook Cournot oligopoly with homogenous products, linear demand and constant unit costs (Theocharis, 1960).[1]

Casual inspection of Cournot market experiments indicates that such markets are characterized by an oscillating adjustment path that differs distinctly from the 'drift' typical of Bertrand markets (see e.g., Davis, 2002, or Heemeijer, Hommes, Sonnemans and Tuinstra, 2009). Nevertheless, behavioral evidence on the stability of Cournot markets is mixed. On the one hand, some investigators report a failure of play to

[1] In such instances, factors such as inertia in the quantity adjustment process or imperfect product substitutability may be added to the market to satisfy the contraction condition (Fisher, 1961).

converge to static Nash predictions in designs where the contraction condition is not satisfied (e.g., Cox and Walker, 1998, Rassenti et al. 2000). On the other hand, in an experiment conducted explicitly to examine the effects of satisfying or not satisfying the contraction condition, Huck, Norman and Oechssler (2002) report essentially indistinguishable levels of convergence to static Nash predictions in both 'stable' and 'unstable' treatments.[2]

Largely missing from this analysis is an examination of the *relative* convergence properties of Bertrand and Cournot markets. More specifically, given a fixed underlying demand and cost structure, what are the convergence consequences of the 'price drift' characteristic of Bertrand markets, relative to the sometimes questionable stability properties of Cournot markets? This is an important policy question. In matters of institutional design, for example, the selection of price or quantity interactions may be an important degree of freedom and it would be well to understand the implications for convergence and stability of the option selected.[3] Again, given heterogeneous decision-makers, the structure of strategic interactions has been shown to importantly affect the responsiveness of markets to nominal shocks, both as a theoretical matter (e.g., Halitwanger and Waldman, 1985, 1989), and in some experimental research (Fehr and Tyran, 2008). It would be well to know if these results apply to the standard oligopoly structures economists use to model imperfectly competitive markets.

This paper reports an experiment conducted to examine the effects of altering the strategic variable between price and quantity on convergence properties in standard differentiated-product oligopolies. The experiment follows a 2×2 design, where treatments are combinations of the strategic variable (price or quantity) and the degree of product substitutability. Variations in product substitutability may impact relative convergence tendencies in two ways. First, as just discussed, when products become sufficiently close substitutes Cournot markets fail Adaptive Learning, and for this reason may become behaviorally unstable. Second, in Bertrand markets increases in product substitutability raise the costs of deviations from best responses, which may be

[2] Huck, Norman and Oechssler (2002) use a probabilistic quantity adjustment rule to generate theoretical stability in a theoretically unstable base design.

[3] Although it is perhaps more typical to conceive of sellers as competing on the basis of price than quantity, interest in Cournot interactions is widespread. For example, Daughtey (2008) discusses some 150 papers published between 2002-2006 that assume Cournot interactions.

interpreted as the costs of decision errors. Increases in such costs may enhance the convergence properties of Bertrand markets. Although changes in product substitutability do not affect the costs of decision errors in Cournot markets, such costs are always higher in Bertrand markets than in Cournot markets (as long as products are not completely unrelated), and these costs increase as products become closer substitutes.

We also explore the relative response of Bertrand and Cournot markets to a nominal shock by pausing each session midway through and publicly announcing a reduction in cost and demand curves. The anticipated response of sellers in different treatments to a nominal shock are similar to anticipated differences in initial market adjustment speeds, but with the difference that a history of play at the pre-shock equilibrium provides a reference point that allows psychological factors such as anchoring and money illusion to further retard the convergence process in Bertrand markets, by enhancing the 'drift' from the old equilibrium to the new one.[4] Experimental evidence by Fehr and Tyran (2008) suggests that these psychological factors can importantly slow convergence in contexts like Bertrand markets where actions are strategic complements rather than strategic substitutes.

By way of overview, similar to Huck, Norman and Oechssler (2002), we find that satisfaction or failure to satisfy Adaptive Learning does not affect Cournot markets. On the other hand, changes in decision errors costs do importantly affect Bertrand markets and for this reason organize most results. In initial 'pre-shock' sequences Bertrand markets deviate from static Nash predictions by smaller amounts initially than Cournot markets, and converge to static Nash predictions more completely. Moreover, when decision error costs are high (e.g,. when products are close substitutes), the reference point of the initial equilibrium does not importantly affect the post-shock adjustment process in Bertrand markets. To the contrary, in the case of close substitutes, Bertrand markets respond more quickly and completely to an announced nominal shock than Cournot markets. However, as products become less closely related, the generally superior convergence tendencies of Bertrand markets weaken. These effects are most

[4] In this context, money illusion means that subjects mistake nominal earnings for real earnings. Given a negative shock, subjects resist adjustment to the new equilibrium to avoid a reduction in perceived earnings. Anchoring refers to a tendency for actors to key off a reference choice when uncertain about the appropriate or optimal adjustment (e.g,. Tversky and Kahneman, 1974), slowing adjustment to the optimal solution.

pronounced following a nominal shock, and in our ‘low substitutability’ design, we can no longer conclude that Bertrand markets converge more completely than Cournot markets post-shock. Rather than an adjustment inertia, however, we attribute the weaker post-shock convergence of Bertrand markets to an increased tendency toward tacit collusion in Bertrand markets as product substitutability weakens.

The remainder of this paper is organized as follows. Section 2 reviews the pertinent literature. Section 3 presents the experiment design and procedures. Results are presented in section 4, followed by some discussion of bounded rationality and market convergence in a fifth section. A short sixth section concludes.

2. Literature Review

A limited experimental literature examines the effects of switching the strategic variable given underlying demand and cost conditions. Altavilla, Luini and Sbriglia. (2006) and Huck, Norman and Oechssler (2000) examine the effects of variations in market feedback on the relative performance of Cournot and Bertrand markets. The primary finding in these investigations is that ‘EXTRA’ information regarding rivals’ individual action choices and earnings outcomes drives Cournot outcomes toward competitive levels, as predicted by Vega-Redondo (1997). Davis (2002) similarly varies information conditions, but focuses primarily on the effects of alterations in the strategic variable on the predictive power of the antitrust logit model (‘ALM’), a simulation model used by antitrust authorities to help identify problematic horizontal mergers. None of these studies, however, focus on convergence properties of the alternative market structures.

Perhaps more pertinent to the present study are a pair of experimental papers by by Heemeijer, Hommes, Sonnemans and Tuinstra (2009, ‘*HHST*’) and Fehr and Tyran (2008, ‘*FT*’) that study the effects of altering actions between strategic substitutes and strategic complements on convergence speeds and levels. *HHST* examines a series of six-seller ‘prediction’ markets, where sellers earn profits by forecasting the next period price more accurately than their rivals. The experiment consists of two treatments, which differ only in the strategic relation between seller forecasts and the induced market price response. In a ‘positive feedback’ treatment, prices move directly with forecasts, making forecasts strategic complements. In the negative feedback treatment the reverse is true, making forecasts strategic substitutes. The authors report significantly higher convergence in the 'negative feedback' treatment.

HHST explain their results as a consequence of bounded rationality. Theoretical work by Haltiwanger and Waldman (1985) shows that for a given share of boundedly rational agents, the extent to which actions are strategic substitutes affects the speed of adjustment towards equilibrium. Intuitively, in contexts where actions are strategic substitutes, rational players have an incentive to move away from boundedly rational (adaptive) players, thus driving outcomes toward the equilibrium. In contrast, when actions are strategic complements, rational players optimize by moving toward the expected actions of the boundedly rational players, slowing convergence. For purposes of conciseness, in what follows we term the enhanced convergence properties of contexts where actions are strategic substitutes rather than strategic complements the 'Strategic Substitutes Effect'.

FT investigates the effects of alterations in the strategic relationship of actions on market responses to a fully announced nominal shock. These authors test the relative effects of strategic complements and strategic substitutes in a stylized four seller discrete choice price-setting game where the static Nash equilibrium is Pareto optimal. The game is presented to participants in a bi-matrix format that shows sellers the own profit consequences of their own and others' average price choices. Each session consisted of two fifteen-period sequences. At the conclusion of the first sequence, the investigators induce a shock that reduces the equilibrium price by half. At the same time, to keep the shock purely nominal, the investigators double the lab/currency exchange rate. To ensure that participants understood the consequences of the shock, they were given a new set of tables, and an opportunity to study them.

FT report dramatic treatment effects in response to the shock. In the strategic substitutes treatment, adjustment to the new equilibrium was, for a large majority of participants (67%), immediate. In contrast, in the strategic complements treatment less than a quarter of participants (23%) adjusted immediately to the shock, and sellers needed ten periods to match the first period equilibrium play rate observed in the strategic substitutes treatment.

In part, *FT* attribute their results to the strategic substitutes effect discussed above as support for the results in *HHST*. Complementing this effect, *FT* argue that the psychological forces of money illusion and anchoring provide yet further reasons for adjustment inertia following a nominal shock in contexts where actions are strategic complements, since these forces induce some sellers to view the previous equilibrium price as a reference for future action. Analyzing individual forecasts and prices, however, *FT* further argue that the nature of strategic interactions itself affects rationality, because strategic complementarity tends to make subject expectations less forward looking, and thus less rational. When actions are strategic complements, they argue, the optimal response to a given deviation from the underlying equilibrium tends to be quite small (e.g,. is quite close to mimicking the expected deviation), making the costs of adaptive expectations relatively small. On the other hand, when actions are strategic substitutes, the optimizing response to a disequilibrium action choice is a large distance from the choice (e.g., on the opposite side of the underlying Nash Equilibrium), raising the costs of adaptive expectations. Thus, *FT* conclude, when actions are strategic substitutes, adaptive sellers commit larger errors, which stimulates a more rapid adjustment of expectations.

Importantly, however, neither *HHST* nor *FT* compare Bertrand and Cournot markets. Parameters in each design are set so that all markets are uniformly stable in the sense that they satisfy Adaptive Learning and so that the costs of decision errors remain constant across treatments. As discussed in the next section, holding demand and cost conditions constant, these conditions necessarily change when shifting the strategic variable between price and quantity.

3. Experiment Design and Procedures

3.1 Experiment Design. To analyze the relative convergence properties of Bertrand and Cournot markets we use a variant of the differentiated-product quadropoly designs studied previously by Huck, Norman and Oechssler (2000) and Davis (2002). The differentiated product design is useful in that it allows a symmetrical variation of product substitutability conditions in a way that variously satisfies or fails to satisfy Adaptive Learning in Cournot markets. Further, laboratory markets with at least four sellers are typically presumed to be relatively immune from tacit collusion, a factor that allows us to focus on convergence properties.[5]

Consider then a four seller market where each firm produces with no fixed costs and with identical marginal costs, *c*. Each firm *i*'s objective function may be written as

$$\pi_i = (p_i - c)q_i\,, \tag{1}$$

where firm *i* optimizes either p_i or q_i, depending on the nature of interactions. Assume that each firm produces a distinguishable product, with inverse demand given by

$$p_i = a - q_i - 3\theta\bar{q}_{-i}\,. \tag{2}$$

In (2) $\bar{q}_{-i}$ is the average quantity choice of the other three sellers, and $\theta \in [0, 1)$ reflects the substitutability between products, with products becoming perfect substitutes as θ approaches 1.

For a comparable price setting game, sellers optimize (1) with respect to price, which requires solving the demand function in (2) in terms of prices. Solving (2) for quantities yields

$$q_i = \tilde{a} - \alpha p_i + 3\beta\bar{p}_{-i} \tag{3}$$

where $\bar{p}_{-i}$ is the average price choice of the other players, and where $\tilde{a} = \dfrac{a}{1+3\theta}$,

$\alpha = \dfrac{1+2\theta}{(1-\theta)(1+3\theta)}$ and $\beta = \dfrac{\theta}{(1-\theta)(1+3\theta)}$. Observe that the restriction $0<\theta<1$ implies that $\alpha>\beta$.

To develop static equilibrium price, quantity and profit predictions for the Cournot game, insert (2) into the expression for p_i in (1) and optimize. Setting $q_j = q_i$ and solving yields the symmetric equilibrium quantities, prices and profits,

$$q_i^c = \frac{a-c}{2+3\theta} \tag{4a}$$

$$p_n^c = \frac{a+c[1+3\theta]}{2+3\theta} \tag{4b}$$

[5] For example in his meta-analysis of factors affecting tacit collusion in market experiments Engel (2006) constructs a 'CN' index that allows a comparison across experiments. Assessing the effects of seller concentration on tacit collusion, Engel summarizes as follows: "The CN index supports the experimentalist view (that two are few and four are many). There is a positive deviation (from the Nash equilibrium prediction) in duopoly and triopoly and a negative deviation in markets of 4 and 5." (p. 15).

and

$$\pi_N^c = \frac{(a-c)^2}{(2+3\theta)^2}. \tag{4c}$$

Similarly, static equilibrium price, quantity and profit predictions for the Bertrand game may be developed by inserting (3) for q_i in (1), and optimizing with respect to price. In the symmetric equilibrium, quantities, prices and profits are,

$$q_n^b = \alpha(\frac{\tilde{a} + c(3\beta - \alpha)}{2\alpha - 3\beta}) \qquad = \qquad \frac{1+2\theta}{(2+\theta)(1+3\theta)}[a-c] \tag{5a}$$

$$p_n^b = \frac{\tilde{a} + \alpha c}{2\alpha - 3\beta} \qquad = \qquad \frac{a(1-\theta) + (1+2\theta)c}{2+\theta} \tag{5b}$$

and

$$\pi_n^B = \frac{\alpha(\tilde{a} + 3\beta c - \alpha c)^2}{(2\alpha - 3\beta)^2} \qquad = \qquad \frac{(1+2\theta)(1-\theta)}{(2+\theta)^2(1+3\theta)}(a-c)^2. \tag{5c}$$

The rightmost terms in (5a) to (5c) are Bertrand predictions expressed in terms of Cournot parameters.

Linear Cournot and Bertrand games with constant costs and a given demand system are distinguishable in that the static equilibrium for the Cournot game involves smaller quantities and higher prices (e.g., Vives, 1999). In the above system, this can be seen by comparing equations (4a) and (4b) with the right side of equations (5a) and (5b). For any $0<\theta<1$, (4a) < (5a), and (4b) >(5b).

Given cost and demand conditions, best response functions for Cournot and Bertrand sellers differ in both sign and absolute value. To see this, find the best response function for the Cournot game by inserting (2) into the price expression (1). Optimizing with respect to q yields

$$q_i = \frac{a-c}{2} - \frac{3\theta\overline{q}_{-i}}{2}. \tag{6}$$

Similarly, the best response function for the Bertrand game is derived by inserting (3) into the quantity expression in (1) and optimizing with respect to p,

$$p_i^b = \frac{\tilde{a} + \alpha c}{2\alpha} + \frac{3\beta\overline{p}_{-i}}{2\alpha} \qquad = \qquad \frac{a(1-\theta) + (1+2\theta)c}{2+4\theta} + \frac{3\theta\overline{p}_{-i}}{2+4\theta}. \tag{7}$$

Comparing the slopes of (6) and (7), note that the algebraic signs are different, reflecting the strategic substitutability of actions in the Cournot game, in equation (6), and the strategic complementarity of actions in the Bertrand game, in equation (7). Note also that the absolute magnitudes of the best response function slopes differ across Bertrand and Cournot environments. Taking the ratio of the best response function slopes in (7) and (6) yields $\frac{2}{2+4\theta}$ in absolute value. This ratio can be unitary only when products are unrelated (e.g., θ=0). As products become closer substitutes (e.g., as $\theta \to 1$) the slope of the Bertrand function becomes relatively flatter.

Holding constant the algebraic sign of the reaction function slope, changes in the slope magnitude do not directly affect predicted convergence properties. However, two related consequences of changes in product substitutability do potentially affect predicted convergence. First, a high degree of substitutability makes Cournot markets theoretically unstable. Observe from (6) that for θ >2/3, the slope of the reaction function for Cournot markets in (6) exceeds 1 in absolute value, thus violating the contraction condition needed to satisfy Adaptive Learning.

Second, in Bertrand markets increases in θ raise the costs of deviating from Nash play. In a price setting environment, the profits associated with a price deviation Δp_i from p_{BR} are

$$\pi_{BR} + \Delta\pi = (p_{BR} + \Delta p - c))(q_{BR} + \Delta q(\Delta p)) \tag{8}$$

Subtracting out π_{BR} yields

$$\Delta\pi = \Delta p(q_{BR} + \Delta q(\Delta p)) + \Delta q(\Delta p)(p_{BR} + \Delta p - c)\,. \tag{9}$$

Expressing q_{BR} in terms of p_{BR} via equation (3), substituting p_{BR} for (7), and observing that $\Delta q(\Delta p)$ = -$\alpha\Delta p$, (9) reduces to

$$\Delta\pi^b = -\alpha\Delta p_i^2 \quad = \quad -\frac{1+2\theta}{(1-\theta)(1+3\theta)}\Delta p_i^2\,. \tag{10}$$

As can be seen from the right hand expression of (10), the costs of a given deviation from best response in a Bertrand game moves directly with θ.

Changes in product substitutability do not similarly affect the costs of deviations in Cournot markets. Making a series of substitutions for the Counot game similar to (8) – (10) yields

$$\Delta\pi^c = -\Delta q_i^2\,, \tag{11}$$

which remains constant for any θ. Moreover, observe that unless products are unrelated (θ=0), Bertrand markets inherently have relatively higher deviation costs than Cournot markets: for any positive θ the coefficient Δp_i^2 in (10) exceeds the unitary constant on Δq_i^2 in (11).

In an important sense, these deviation costs may be viewed as the costs of decision errors. A large behavioral literature documents the effects of decision error costs on convergence to a Nash equilibrium. See in particular the literature on the Quantal Response Equilibrium, such as Rosenthal (1989), McKelvey and Palfrey (1995) and Anderson et al. (1998, 2001). The relatively higher costs of deviations in Bertrand markets may counteract to a greater or lesser extent the much larger magnitude of best replies in games with strategic substitutes that *FT* argue endogenously induce rationality.

To examine the effects of changes in product substitutability on convergence and responsiveness to nominal shocks, we consider θ=0.5 and θ=0.9, roughly equal round number deviations from the contraction condition boundary of θ=0.67. To complete the design parameterization we initially set a=80, and c=8. These parameters yield the static Nash predictions for each treatment summarized in the upper 'pre-shock' portion of Table 1. In column (1) of the table, we identify treatments as combinations of the strategic interaction type ('*B*' for Bertrand and '*C*' for Cournot) and the degree of product substitutability ('*H*' for θ = 0.9 and '*L*' for θ = 0.5). Thus, for example, '*BL*' in the top row of Table 1 lists Bertrand market predictions for the case where θ=0.5.

Notice from column (2) in the pre-shock portion of Table 1 that under both substitutability conditions the Walrasian and joint maximizing prices are p_w=\$8 and p_{JPM} =\$44, respectively. Comparing columns (2) and (3) across row blocks, observe further that increasing product substitutability reduces Nash equilibrium prices for both Cournot and Bertrand markets. Further, within row blocks, static Nash predictions for Bertrand markets involve lower prices and higher quantities than for comparable Cournot markets, as is standard. For example, in the low substitutability regime shown top row block of the table Bertrand and Cournot Nash equilibrium prices are p_b =\$22.40 and p_c= \$28.57, respectively. In the high substitutability regime shown in the second row block, Bertrand and Cournot Nash equilibrium prices are p_b =\$10.48 and p_c= \$23.32.

To examine the response to an announced nominal shock, we stop the session after period 40 and announce a shift in the intercept and unit costs to a=40, and c=4, along with a quadrupling of the conversion lab/U.S. dollar conversion rate for a second 'post-shock' 40 period sequence.[6] The bottom portion of Table 1 lists reference Nash equilibrium predictions for each treatment in the post-shock sequences. Notice in all treatments that all price and quantity predictions fall by exactly half relative to the pre-shock phase.

3.2 Conjectures. We are interested in assessing two features of relative market performance (a) *initial adjustment*, or how quickly markets in one treatment adjust either at the outset of a sequence or following a shock, relative to markets in another treatment and (b) *ultimate convergence* or the degree to which markets in one treatment ultimately approach to the static Nash equilibrium prediction for their treatment, relative to the ultimate approach of markets to the static Nash prediction for another treatment.

Consider first our expectations regarding initial adjustment and ultimate convergence for the *BL* and *CL* treatments. Both of these treatments markets satisfy Adaptive Learning. To the extent that the above-discussed Strategic Substitutes Effect dominates other pertinent factors in oligopoly games, we would anticipate faster and more complete convergence in the *CL* markets. On the other hand, the relatively higher decision error costs in Bertrand markets works against the Strategic Substitutes Effect. Column (5) of Table 1 provides some sense of the higher deviation costs in the *BL* markets. In the *BL* markets a unilateral price deviation equal to 5% of the Walrasian to joint maximizing range costs a seller 0.60% of Nash equilibrium earnings. In contrast, in the *CL* markets a comparable percentage unilateral quantity deviation costs a seller just 0.25% of Nash equilibrium earnings. Of course, the larger magnitude of best replies in the Cournot markets offsets the higher opportunity costs of a given deviation in Bertrand markets. Nevertheless, the relatively higher costs of decision errors in the *BL* treatment provide a basis for viewing the relative convergence of *BL* and *CL* markets as an open

[6] We quadruple rather than double the exchange rate here because we reduce by one half both the static equilibrium prices and quantities. Changing only price biases results in favor of Cournot markets since quantity-selecting sellers who completely ignore a nominal price shock would remain in equilibrium were they to post the initial equilibrium quantity post-shock.

question. These observations form a first conjecture, which we state as a null hypothesis to emphasize the open nature of this research question.

Conjecture 1(a)*: When θ =0.5 the use of Bertrand rather than Cournot interactions affects neither initial market adjustment nor ultimate market convergence.*

Related, but not identical to the relative convergence properties of Bertrand and Cournot markets in initial market sequences is the responsiveness to an announced nominal shock. A history of repeated play at (or at least close to) the pre-shock equilibrium creates anchoring and money illusion effects that that *FT* report particularly hinder convergence in contexts where actions a strategic complements. We state this as a second part of conjecture 1.

Conjecture 1(b)*: When θ =0.5 the use of Bertrand rather than Cournot interactions affects neither the initial market adjustment to an announced nominal shock nor ultimate market convergence.*

Two additional conjectures regard the effects of increased product substitutability. First, in the Cournot treatments raising θ above *0.67* violates Adaptive Learning in Cournot markets. To the extent that violation of this condition affects the convergence properties of Cournot markets, we should observe both slower and less complete convergence in the *CH* treatment relative to the *CL* treatment. This is a second conjecture, which given an unambiguous directional prediction, we state in alternative hypothesis form.

Conjecture 2*: Increasing θ from 0.5 to 0.9 slows both the initial adjustment and ultimate convergence levels in Cournot markets.*

Next, in the Bertrand treatments increasing θ raises decision error costs. Over the θ range considered here these effects are pronounced. For example, as seen in column (5) of Table 1 the cost of a deviation from the Nash price equal to 5% of the Walrasian to Joint Maximizing range increases from 0.60% of Nash earnings when θ = 0.5 to 4.46% of Nash earnings when θ=0.9. Although changes in the cost of decision errors may slow the initial adjustment process, there is no reason *a priori* to suspect that these will affect ultimate convergence. The effect of increases in the costs of decision errors is a third conjecture, which we also state in alternative hypothesis form.

Conjecture 3*: Increasing θ from 0.5 to 0.9 speeds the initial adjustment in Bertrand markets, but does not affect ultimate convergence.*

Combined, conjectures 2 to 3 suggest that as θ increases convergence speeds and levels should improve in Bertrand markets relative to Cournot markets. These should improve both initially, and following a shock. Nevertheless, despite the predicted directional effects of Conjecture 2 and 3, we cannot necessarily anticipate absolutely better convergence properties in Bertrand markets when $\theta =0.9$, either pre- or post-shock. Thus, we offer as a fourth and final conjecture, the following, which, like conjecture 1, we state in null hypothesis form, and in two parts.

Conjecture 4(a)*: When $\theta =0.9$ the use of Bertrand rather than Cournot interactions affects neither initial market adjustment nor ultimate market convergence.*

Conjecture 4(b)*: When $\theta =0.9$ the use of Bertrand rather than Cournot interactions affects neither the initial response to a nominal shock nor ultimate market convergence.*

3.2 Experiment Procedures. The experiment consists of a series of 24 forty-period quadropolies, with six markets in each market type/ degree of product substitutabilty treatment cell. To increase anonymity, markets are conducted in pairs. At the start of each session, eight participants are randomly seated at visually isolated computer terminals. After seating, a monitor reads instructions aloud as participants follow along on copies of their own. The instructions explain that each period sellers simultaneously submit price (quantity) decisions as well as forecasts of others' mean price (quantity) choices on a continuous choice grid. In the Cournot game, sellers are restricted to the quantity range $q \in [0, 50]$, under the condition that the minimum prices implied by the aggregate quantity choices do not fall below unit costs. Symmetrically, in the Bertrand game, sellers make price choices over the range $p \in [8, 50]$.[7] Forecasts are submitted under the condition that sellers earn a small 'forecasting prize' each period the forecast is sufficiently accurate.[8] Once all decisions are complete, an automated buyer makes

[7] Implied minimum price restrictions in the Cournot markets kept sellers from realizing losses. Maximum prices in Bertrand markets were imposed to keep sellers from inflating rival earnings with excessively high price signals. Huck, Normann and Oechssler (2000) show that such truncations do not affect equilibrium predictions. as long as the truncated interval includes the Walrasian to joint-maximizing range.

[8] 'Accurate' is within \$0.30 of the subsequently observed others' mean price choice in the Bertrand markets and within 0.20 units of the subsequently observed others' mean quantity choice the Cournot markets. The narrower range for the forecasting game in the Cournot markets reflects the narrower effective choice space

purchase decisions in accordance with the appropriate demand condition in Table 1. At the end of each trading period, participants receive as feedback the average action choice of the other sellers, whether or not they won the forecast prize, and their own earnings, both for the period, and cumulatively.

In addition to explaining the price (quantity) posting and feedback procedures, instructions present to sellers as common information demand and cost conditions as well as the number of periods in the market. To help them better understand their induced demand condition we gave participants a profit calculator that allowed them to evaluate the earnings consequences of hypothetical own and average others' action choices.

After giving participants an opportunity to privately ask any questions they might have, the market begins. Following period 40 the session is paused, and a shock is announced. Specifically we announce a shift in the intercept and unit costs to a=40, and c=4, along with a quadrupling of the conversion lab/U.S. dollar conversion rate for a second 'post-shock' 40 period sequence. After the second treatment, participants are privately paid the sum of their earnings from the two sequences plus a $6 appearance fee, and dismissed one at a time.

Participants were 96 undergraduate students enrolled in upper level business courses at Virginia Commonwealth University in the spring semester of 2008. No participant had previous experience with a linear oligopoly market, and no one participated in more than a single session. Conversion rates were varied across treatments in order to hold expected payoffs roughly constant across treatments. In initial periods we used a conversion rate of $1800 dollars = $1 U.S. in the Cournot markets with θ=0.5 and $1400 lab =$1 U.S. in the Bertrand markets with θ=0.5. When θ=0.9 lab dollar earnings were converted to U.S. currency at a rate of $1000 lab = $1 U.S. in the Cournot markets and $200 lab =$1 U.S. in the Bertrand markets. Post shock, the lab dollar/ U.S. currency conversion rate was quadrupled in all treatments. Earnings for the 70-90 minute laboratory sessions, inclusive of a flat $6 payment for making their scheduled appointment, ranged from $13 to $40, and averaged $23.75.

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in those markets, as can be seen by comparing the price and quantity differences between Walrasian and joint maximizing outcomes in Table 1. The size of the forecasting prize was also varied across treatments to maintain an approximately constant absolute and relative saliency of the prize across treatments. With θ=0.9 the per period forecast prize was $10 lab in both the Bertrand and Cournot games. With θ=0.5, the per period forecast prize was $1 lab in the Bertrand game and $5 lab in the Cournot game.

4. Results

The mean transaction price paths for each treatment, shown in Figures 1 to 4 provide an overview of experimental results.[9] Looking first at the *BL* and *CL* markets, for the initial sequence, shown in panels (a) of Figures 1 and 2, observe that switching from Bertrand to Cournot interactions elicits the expected effect on price adjustment dynamics in the sense that the rather smooth drift of prices across periods in the Bertrand markets is replaced by a bumpy oscillation of implied prices across periods in the Cournot markets. Notice also, however, that the effects of larger decision cost errors in the *BL* markets appears to dominate the potentially ameliorative effects of strategic substitutes in the *CL* markets, even in this case, when the Cournot markets satisfy Adaptive Learning. Except for a single *BL* 'outlier' market that drifts far above the Nash equilibrium price from periods 18 to 35, convergence is both rapid and complete in the *BL* markets. In contrast, in the *CL* markets deviations from Nash predictions are large and persistent.

Turning to the post-shock sequences for the *BL* and *CL* markets, shown in panels (b) of Figures 1 and 2, notice that here the difference in relative convergence tendencies is less clear, with most of the difference coming from the Bertrand markets. Following the shock convergence to the underlying *NE* appears to be less than complete in several *BL* markets.

Comparing price paths for the *BH* markets in Figure 3 with the *BL* markets in Figure 1, observe that increasing θ clearly improves convergence in Bertrand markets, both pre- and post-shock. Relative to the *BL* treatment, deviations in the *BH* series are smaller initially, and homogenously collapse on the static Nash equilibrium price prediction. On the other hand, comparing transaction prices for the *CH* series in Figure 4 with the *CL* series in Figure 2 observe that increasing θ does not exert the destabilizing effect on Cournot markets predicted in conjecture 2. To the contrary, transaction price paths in the *CH* and *CL* markets do not differ in any obvious way either in either the pre- or post-shock sequences. Finally, comparing across the *BH* and *CH* markets shown in

[9] We display transactions prices rather than quantity choices for the Cournot markets to facilitate a comparison across institutions. (The vertical scale of quantity and price choices differ.) A display of Cournot quantity choices and Bertrand transactions quantities yields similar results.

Figures 3 and 4, observe that when θ=.9 prices convergence much more quickly and completely in the *BH* treatment, both pre-shock and post-shock.

The pairwise comparisons of absolute median price deviations shown in Figures 5 to 8 allow a quantitative evaluation of conjectures 1 to 4. In what follows we assess initial response in terms of differences in absolute median deviations in the first several periods of a sequence (usually the first 10) and ultimate convergence levels in terms of differences in absolute median deviations for the final several periods in a sequence (again, usually the last 10). Looking first the *BL* and *CL* treatments, shown in Figure 5, observe that in the pre-shock sequences, median absolute deviations for the *CL* markets track almost uniformly above their *BL* counterpart. Further, as indicated by the hollow and solid dots printed at the top of the panel, the initial adjustment process in Bertrand markets is more rapid. Using a two-tailed Mann-Whitney test, the null hypothesis that the absolute median deviations in the *BL* and *CL* markets are equal can be rejected at p<.10 in 5 of the first 10 periods (and in 8 of the first 13 periods). Similarly the same null hypothesis can be rejected at p<.05 in 3 of the first 10 periods (or in 5 of the first 13 periods). Differences in ultimate convergence levels, however, are much smaller. In the last 10 periods, the null of no difference across treatments can be rejected in only 3 instances and only at p<.10 in each instance. This is a first finding.

Finding 1(a)*: In the pre-shock sequence initial adjustment in BL markets is more rapid than in CL markets. Ultimate convergence, however, does not differ significantly across the BL and CL treatments.*

Turning to the post-shock sequences for *BL* and *CL* treatments, shown in the right panel of Figure 5, observe that although the absolute median path for the *CL* markets again tracks largely above the *BL* treatment counterpart in initial periods the differences are infrequently significant. For example, the null hypothesis that median absolute deviations in the *BL* and *CL* markets are equal can be rejected at p<.10 in only 2 of the first 10 post-shock periods, and only one of these (in period 1) is significant at p<.05. Evidence regarding differences in ultimate convergence levels is even weaker. Absolute median price deviations across the *BL* and *CL* treatments do not significantly differ at p<.10 in any of the final 10 periods and only once in the last 20 periods. This is a second finding.

Finding 1(b)*: The more rapid initial adjustment of BL markets relative to CL markets does not carry over to periods following an announced nominal shock. Post-shock, ultimate convergence also does not differ significantly across the BL and CL treatments.*

The comparisons of median absolute deviations within market type, shown in Figures 6 and 7, allow evaluation of conjectures 2 and 3, respectively. From the absolute median price deviations for the Cournot treatments, shown Figure 6 observe that, contrary to conjecture 2, changing θ does not behaviorally affect convergence. Both pre- and post-shock, the *CH* and *CL* series largely overlap throughout the session. Using a one-tailed Mann-Whitney test, the null hypothesis *CH* deviations are no larger than their *CL* counterpart can be rejected only occasionally and only in the pre-shock sequence (at $p<.10$ in only five periods and at $p<.05$ only once). Further, these occasional rejections of equal median deviations are scattered throughout the pre-shock sequence and follow no obvious pattern. This is a second result, which parallels related findings by Huck, Normann and Oechssler (2002).

Finding 2: *Increasing θ from 0.5 to 0.9 affects neither initial adjustments nor ultimate convergence in Cournot markets.*

Turning to the median absolute deviations for the Bertrand markets in Figure 7, observe that increasing θ does systematically improve Bertrand market convergence both pre- and post-shock. In the pre-shock periods, median absolute deviations for the *BH* treatment lie consistently below their *BL* counterparts, particularly in initial periods. Using a one-tailed Mann-Whitney test the null hypothesis that median absolute deviations in the *BL* series are no greater than in the *BH* series can be rejected at $p<.10$ in 8 of the first 10 periods, and at $p<.05$ in four of those instances. Toward the end of the sequence, differences become less regular, but even here are still fairly frequent. The same null of no difference across treatments can be rejected at $p<.10$ in 4 periods and $p<.05$ in 3 of those instances.

Post-shock, the enhanced relative convergence tendencies of *BH* markets are even more consistently significant: the null hypothesis that median absolute deviations in the *BL* series are no greater than in the *BH* series can be rejected at $p<.10$ in each of the first 10 periods and at $p<.05$ in 5 of those instances. In the last 10 periods the same null can be rejected at $p<.05$ in all 10 comparisons. This support for conjecture 3 is a third finding.

Finding 3. *Raising θ improves both initial market adjustments and ultimate convergence levels in Bertrand markets. Differences are most persistent in the post-shock sequences.*

The powerful convergence-enhancing effects of increased substitutability in Bertrand markets also have the effect of generating overwhelmingly superior convergence properties for *BH* markets relative to *CH* markets. As seen in Figure 8, not only do the absolute median price deviations in *CH* markets uniformly exceed their *BH* market counterparts, but the differences are almost uniformly significant both initially and in terminal periods. In the pre-shock sequence, the null hypothesis that absolute deviations in *BH* and *CH* sequences do not significantly differ can be rejected at $p<.05$ in each of the first 10 periods. Ultimate convergence levels for the *BH* treatment also appear to be higher. In the last 10 periods the same null can be rejected at $p<.10$ in 5 instances and at $p<.05$ in 3 of these comparisons.

Post-shock, the differences are still more pronounced. Initially, median absolute deviations for the *BH* treatment are significantly smaller than their *CH* counterpart at $p<.05$ in each of the first 10 periods. Similarly, ultimate convergence levels for the *BH* treatment are unambiguously higher. The null of no difference across treatments can be rejected at $p<.10$ in each of the last 10 periods and at $p<.05$ in 9 of those comparisons. These results support a fourth finding.

Finding 4. *Initial adjustments are more rapid and ultimate convergence more complete in the BH markets than in the CH markets. This is true both pre-shock as well as post-shock.*

Prior to closing this subsection, we offer an alternative assessment of ultimate convergence levels by evaluating treatment outcomes in terms of individual decisions. Such an analysis usefully allows distinction of instances where disperse individual actions yield average transaction prices close to Nash predictions, from instances where sellers are homogenously close to making equilibrium plays. More specifically, we assess ultimate convergence levels in terms of the propensity of individuals to make action choices close to the Nash equilibrium choice. Defining a ‘neighborhood’ as a percentage of the range between Walrasian and joint-maximizing outcomes, we report in column (1) of Table 2 the average percentage of individual choices within 5% and 10% neighborhoods of the static Nash equilibrium action for the last 10 periods of the pre-shock and post-shock sequences.[10] Starting with the pre-shock sequence, shown in the upper panel, observe first the essentially complete convergence of the *BH* treatment. For this treatment 90% of plays are within 5% of the Nash equilibrium, a level that is both high absolutely, and relative to the other treatments. The comparable average for the *BL* treatment (of 52%) is 38 percentage points lower, which in turn exceeds the comparable averages for either of the Cournot treatments by another 23 to 25 percentage points. As indicated in columns (4), (5) and (6), all of these across-treatment differences are significant at $p<.05$ using a two-tailed Mann-Whitney test.

Results for the broader 10% neighborhood about the Nash equilibrium, shown in the second row block in Table 2, provides a basis for distinguishing the *BL* markets from the Cournot treatments. Over the last 10 periods, 80% of action choices in the *BL* markets satisfy this weak convergence standard, compared to only 47% and 37% for the *CH* and *CL* markets, respectively. The mean differences between the *BL* markets and the Cournot markets are significant at $p<.05$, using a two-tailed Mann-Whitney test.

That neither Cournot treatment has more than 50% of action choices within 10% of the Nash equilibrium in the final pre-shock periods merits some emphasis. The low level of behavior consistent with Nash equilibrium play even under this weak standard suggests that in the initial periods Cournot markets in a non-trivial sense, remain non-convergent.

Turning to the post-shock sequences, summarized in the bottom half of Table 2, observe that in many respects, the ultimate convergence levels observed in the pre-shock sequences carry over to the post-shock sequences. For the *BH* markets the individual Nash play rates of 90% using a 5% neighborhood and 93% using a 10% neighborhood, virtually duplicate the pre-shock Nash play rate for this treatment. Similarly, in the post-shock sequences the *CL* and *CH* markets remain largely non-convergent. Post-shock, no

[10] The final 10 periods are used to assess ultimate convergence behavior only for purposes of specificity. Results, however, are not terribly sensitive to the choice of the final periods. For example, in Table A1 of an online data appendix, reports results comparable to Table 2 but using the final five periods of each treatment as a basis of comparison. Results are essentially identical to those reported in Table 2.

more than 28% of plays in the last 10 periods are even within 10% of the Walrasian to joint-maximizing quantity range in either Cournot treatment.

The primary difference in pre- and post-shock outcomes is the reduced incidence of Nash plays in the *BL* treatment. For the *BL* treatment the incidence of plays within 5% of the Nash prediction falls from 52% pre-shock to 39% post-shock. Again, the percentage of plays that fall within the broader 10% neighborhood of the Nash prediction falls from 80% pre-shock to 54% post-shock. Although the rate of action choices within 10% of the Nash prediction for the *BL* treatment post-shock remains roughly twice as high as the comparable number for either the *CH* and *CL* treatments, the variability of outcomes within the *BL* treatment make this difference insignificant at $p<.10$. We summarize these observations with the following comment.

Comment 1: *Both pre- and post-shock ultimate convergence levels are very high in BH markets and are uniformly so low in the Cournot treatments that the Cournot markets may, in a non-trivial sense, be regarded as 'non-convergent.' In the BL treatment markets exhibit significantly higher ultimate convergence levels than observed in the Cournot treatments pre-shock. Post-shock, however, ultimate convergence levels across the BL and Cournot treatments no longer significantly differ.*

5. Herding Behavior and Tacit Collusion in Oligopolies

The slower and less complete convergence in the *CL* and *CH* treatments relative to the *BL* and then to the *BH* treatment is consistent changes in decision error costs across treatments listed in column (4) of Table 1. These results differ starkly from the superior performance of contexts where actions are strategic substitutes rather than strategic complements observed by *FT* and *HHST*, and the pattern of outcomes lead us to broadly conjecture that in oligopoly contexts, changes in decision error costs dominate the Strategic Substitutes Effect. However, other differences exist between the oligopoly context we examine here and the more stylized environments examined by *FT* and *HHST*, and these design differences may interact with changes in decision error costs across treatments in a way that contributes to the observed outcomes. In this subsection we consider two such differences, herding behavior, and tacit collusion.

5.1 Herding Behavior in an Oligopoly Environment. In both *HHST* and *FT*, sellers almost uniformly made best responses to their forecasts of rival behavior (In *HHST* sellers submitted forecasts and best responses were 'hard-wired' into the design. In *FT*, the bi-matrix structure of game made best responses an overwhelmingly dominant choice.) Best response behavior is far less standard in oligopoly games. Indeed, Huck, Norman and Oechssler (2002) attribute the unpredicted stability observed in an 'unstable' Cournot design to a propensity of sellers to imitate the anticipated actions of their rivals.

'Herding' behavior of this type is a natural response of players who are uncertain as to how to play. In comparing Cournot to Bertrand environments, however, we observe that sellers' propensities to follow an imitation strategy injects far more variability into the former, because the difference between an anticipated action and the best response to that action is far greater in the Cournot environment.

The four panels of Figure 9, which plot the response of sellers to their forecast of rival actions in the first 10 periods after the shock illustrates. In the *BL* and *BH* treatments, shown in the left panels, the relation between actions (shown as individual markers) and best responses (shown as a solid line) is quite high because the distance between copying of rivals' anticipated actions (shown as a dashed line) and the best response to those actions are quite small. The correlations between prices and best responses in the *BL* and *BH* treatments are strongly positive, at .83 and .77, respectively.[11] In stark contrast, in the *CL* and *CH* treatments, shown as the right panels, the correlations between rival quantity forecasts and best responses are strongly negative at -.65 and -.60, respectively, because many sellers imitate the expected actions of rivals rather than best respond to those expectations.

Our point here is not that Bertrand markets induce rationality. To the contrary, we believe that the rationality of participants is largely independent of the nature of strategic interactions.[12] Rather, we observe that the difference between imitating and best responding to rivals' expected actions is small and decreasing as products become closer

[11] The correlation reported for the *BH* treatment omits the four outliers in the lower left panel of Figure 9 that were obvious price signals. Further for all treatments we eliminate a limited set of forecasts that are out of the range of possible action choices (e.g., prices or quantities above 50). Finally, the scattergrams in Figure 9 use data from periods 41-50 for purposes of specificity. The tendency to imitate rather copy forecasts however, is quite general. Figure A1 in an online appendix illustrates comparable scattergrams for periods 1-10. Responses in these initial periods are generally more dispersed that those shown in Figure 9. However, correlations between forecasts and actions are very similar to those reported in the text, particularly in the respect that they are large and positive in the Bertrand markets and large and negative in the Cournot treatments

[12] In fact, in Table A2 of an online appendix we show that the relative proximity of action choices to best responses and imitation are roughly equal in all treatments.

substitutes in Bertrand markets, while in Cournot markets, the difference between ‘imitating’ and best responding to rivals actions is large and increasing as products become closer substitutes. The capacity of sellers to ‘herd’ rather than best respond to others’ anticipated actions in standard oligopoly contexts importantly and persistently impedes the adjustment process for Cournot competitors. We summarize these observations as the following comment.

Comment 2. *A propensity for sellers to imitate rivals’ expected action choices importantly undermines convergence in Cournot markets. The effects of imitation are more pronounced in Cournot than in Bertrand markets because the distance between best responses and forecasts are far larger in the Cournot markets.*

5.2 Tacit Collusion in Bertrand Markets. A second difference between our oligopoly markets and the designs studied in *FT* and *HHST* is that in our markets, the static Nash equilibrium is not a Pareto dominant outcome, so sellers can increase earnings by successfully coordinating tacitly. Looking back at the mean contract price series in Figures 1 to 4, we observe that a propensity for prices to drift above the static Nash equilibrium occurs most obviously in the *BL* treatment. In this treatment, a single outlier market deviates above the static Nash prediction pre-shock. Post shock, several markets drift above the static Nash prediction for many periods. Both pre- and post-shock, however, the deviations are not a consequence of an initial adjustment inertia, but rather of subsequent pries that persistently exceed the Nash prediction, an outcome we attribute to tacit collusion.[13]

We are certainly not the first to observe an increased propensity to tacit collusion in Bertrand markets. In a meta-analysis of experiments examining Cournot and Bertrand market competition Suetens and Potter (2007) conclude that Bertrand markets are more susceptible to tacit collusion than Cournot markets. Potters and Suetens (2009) subsequently report duopoly experiment designed to isolate the effect of changing the

[13] Closer consideration of action choices supports the conclusion that the observe price drift in the *BL* markets is attributable to tacit collusion, in the sense that the prices are the result of consistent seller signaling behavior. Table A3 in an online appendix records for each session of each treatment two types of action signals, ‘spikes’ and ‘surges’. Spikes are large deviations which reduce expected sales to zero, while surges are smaller, but more persistent price increases (or quantity reductions). Overall, Bertrand sellers engage much more signaling activity than Cournot sellers. Within Bertrand markets, repeated price ‘surges’ which are much more prevalent in the *BL* treatment, are strongly correlated with instances of high transaction prices.

form of strategic interactions on the propensity of sellers to tacitly collude and find that holding all else equal average cooperation levels are more than twice as large under complementarity than under substitutability.[14] Our results contribute to these previous findings in two respects. First, the incidence of tacit collusion in Bertrand markets is not constant, but rather increases as products become weaker substitutes. Decreased substitutability both reduces the costs to sellers of signaling an intention to cooperate as well as the benefits of deviating from a cooperative arrangement.[15] In our *BH* treatment, where 'signaling costs' are very high, we observe no greater tendency for tacit collusion to affect prices than in either Cournot treatment.

Second, we observe an increased incidence of tacit collusion in the *BL* treatment in the post-shock periods. Although our sample is small, we speculate that this outcome is due to a sort of 'money illusion' effect: sellers, accustomed to high nominal earnings find natural efforts to coordinate on prices that restore nominal earnings to their pre-shock levels. Interestingly, this consequence of 'money illusion' differs from that suggested by *FT* in that it affects not the immediate response to a shock (indeed all but one of the *BL* markets adjusted to the post shock equilibrium within a few periods), but to a propensity of sellers to try and coordinate in the post shock environment. We summarize these observations as a third and final comment.

Comment 3: *Tacit collusion can retard adjustment in Bertrand markets. The propensity toward tacit collusion becomes more pronounced as products are weaker substitutes, and following a nominal shock.*

7. Conclusion

This paper reports an experiment conducted to assess the relative convergence properties of Bertrand and Cournot oligopolies. As a theoretical matter, we observe that countervailing factors make the relative convergence properties of Bertrand and Cournot markets an open question, *a priori*. On the one hand, the 'Strategic Substitutes Effect' observed by *HHST* and *FT* suggests that contexts where actions are strategic substitutes

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[14] As with *HHST* and *FT*, Potters and Suetens (2009) explain their results in terms of bounded rationality: when actions are strategic complements rather than substitutes, rational players optimize by moving toward the actions of the boundedly rational players. In a repeated context, a tendency to copy the actions of other (high pricing) sellers, facilitates tacit collusion.

[15] Davis (2009) makes a similar observation in a homogeneous product context, but where the costs of deviation are varied by increasing excess supply.

(such as a Cournot market) converge more quickly, and respond to announced nominal shocks more fully than contexts where actions are strategic complements (such as Bertrand markets) because when products are strategic substitutes rational agents optimize by moving away from rather than emulating the expected actions of their boundedly rational counterparts. On the other hand, if products are insufficiently differentiated, Cournot markets are unstable in the sense that they do not satisfy the Milgrom and Roberts' Adaptive Learning Criterion. Further, holding demand and seller cost conditions constant, the costs of deviating from a best response are higher in a Bertrand market than in its Cournot counterpart and these deviation costs increase as products become closer substitutes.

Experimental results indicate that in general, the latter of these effects dominates the former, and Bertrand markets converge to Nash equilibrium predictions more quickly and more completely than Cournot markets. Although Cournot markets are largely unaffected by the satisfaction of or failure to satisfy Adaptive Learning, outcomes in Cournot markets remain persistently variable even in final periods of a sequence. In Bertrand markets convergence is generally more complete and improves as products become close substitutes, a result consistent with the high and increasing decision error costs in Bertrand markets. Further, when products are close substitutes, Bertrand markets respond more quickly to an announced nominal shock.

Supplementing the effects of higher decision error costs in Bertrand markets is a tendency in standard oligopoly contexts for many sellers to 'herd' by mimicking the anticipated actions of rivals. Herding behavior particularly affects convergence in Cournot markets because the distance between the anticipated actions of rivals and the best response to those actions is very large. On the other hand, as products become weaker substitutes, an increased tendency for tacit collusion degrades convergence in Bertrand markets. This effect is particularly pronounced following a nominal shock, where the reference outcomes in the pre-shock phase encourage price-signaling activity.

These results are important in that they suggest that the adjustment from price setting Bertrand games to quantity setting Cournot games may have important consequences for market stability. When products are sufficiently close substitutes, a market conducted under Bertrand interactions converges more quickly and completely than if conducted under Cournot interactions. As products become less closely related, the difference becomes less pronounced, due to an increased tendency for tacit collusion in Bertrand markets.

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Table 1. Parameters and Static Nash Predictions

(1)	Static Nash Predictions (2) p_i	(3) q_i	(4) π_i	(5) Deviation Costs[a]
Pre-Shock Sequence				
Low Substitutability (c=8, $p_i = 80 - q_i - 0.5\sum_{j \neq i} q_j \quad q_i = 32 - 1.6 p_i + .4\sum_{j \neq i} p_j$)				
BL	\$22.40	23.04	\$331.78	0.60%
CL	\$28.57	20.57	\$423.18	0.25%
Joint Max.	\$44.00	14.40	\$518.40	
Walrasian	\$8.00	28.80	\$0	
High Substitutability (c=8, $p_i = 80 - q_i - 0.9\sum_{j \neq i} q_j \quad q_i = 21.62 - 7.57 p_i + 2.43\sum_{j \neq i} p_j$)				
BH	\$10.48	18.79	\$46.65	4.46%
CH	\$23.32	15.32	\$234.68	0.25%
Joint Max.	\$44.00	9.73	\$350.27	
Walrasian	\$8.00	19.46	\$0	
Post-Shock Sequence				
Low Substitutability (c=4, $p_i = 40 - q_i - 0.5\sum_{j \neq i} q_j \quad q_i = 16 - 1.6 p_i + .4\sum_{j \neq i} p_j$)				
BL	\$11.20	11.52	\$82.94	0.60%
CL	\$14.29	10.29	\$105.80	0.25%
Joint Max.	\$22.00	7.20	\$129.60	
Walrasian	\$4.00	14.40	\$0	
High Substitutability (c=4, $p_i = 40 - q_i - 0.9\sum_{j \neq i} q_j \quad q_i = 10.81 - 7.57 p_i + 2.43\sum_{j \neq i} p_j$)				
BH	\$5.24	9.39	\$11.66	4.46%
CH	\$11.66	7.66	\$58.67	0.25%
Joint Max.	\$22.00	4.86	\$87.57	
Walrasian	\$4.00	9.73	\$0	

Key: [a] Own earnings lost due to a five percent deviation from the best response to rivals' expected actions, expressed as a percentage of Nash equilibrium earnings.

Table 2. Percentage of Action Choices within a Neighborhood of the Nash Equilibrium, Periods 31-40[a]

(1) Mean	(2) Treatment	(3) *BH*	(4) *BL*	(5) *CH*	(6) *CL*
		Pre-Shock			
5% Neighborhood					
90%	*BH*	--	0.02*	0.00*	0.00*
52%	*BL*		--	0.13	0.11
29%	*CH*			--	0.47
25%	*CL*				--
10% Neighborhood					
95%	*BH*	--	0.05*	0.00*	0.00*
80%	*BL*		--	0.04*	0.01*
47%	*CH*			--	0.33
37%	*CL*				
		Post-Shock			
5% Neighborhood					
90%	*BH*	--	0.01*	0.00*	0.00*
39%	*BL*		--	0.63	0.20
25%	*CH*			--	0.26
16%	*CL*				--
10% Neighborhood					
93%	*BH*	--	0.15	0.00*	0.00*
54%	*BL*		--	0.34	0.29
27%	*CH*			--	0.81
28%	*CL*				--

Key: In each treatment we define a 'neighborhood' as deviations from the Nash equilibrium prediction that are less than or equal to either 5% or 10% of the Walrasian to Joint Maximizing Range. Entries in columns (4) to (6) report *p* values for a test of the null hypothesis that the row and column treatments do not differ. '*'s highlight instances where the treatments at p<.05 using a two tailed Mann-Whitney test.

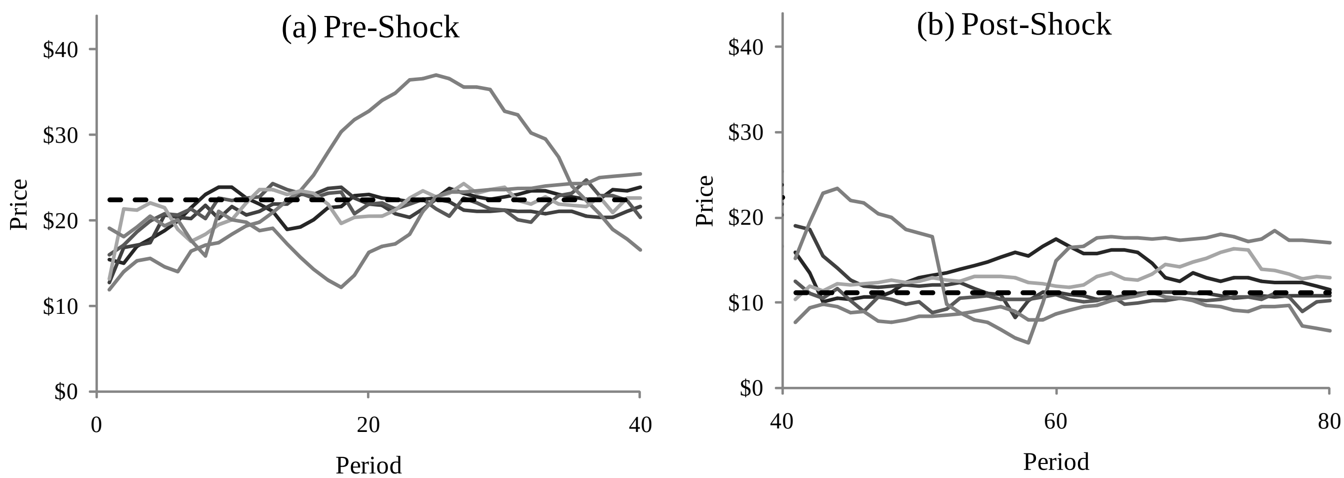

Figure 1. Mean Transaction Prices, *BL* Treatment.

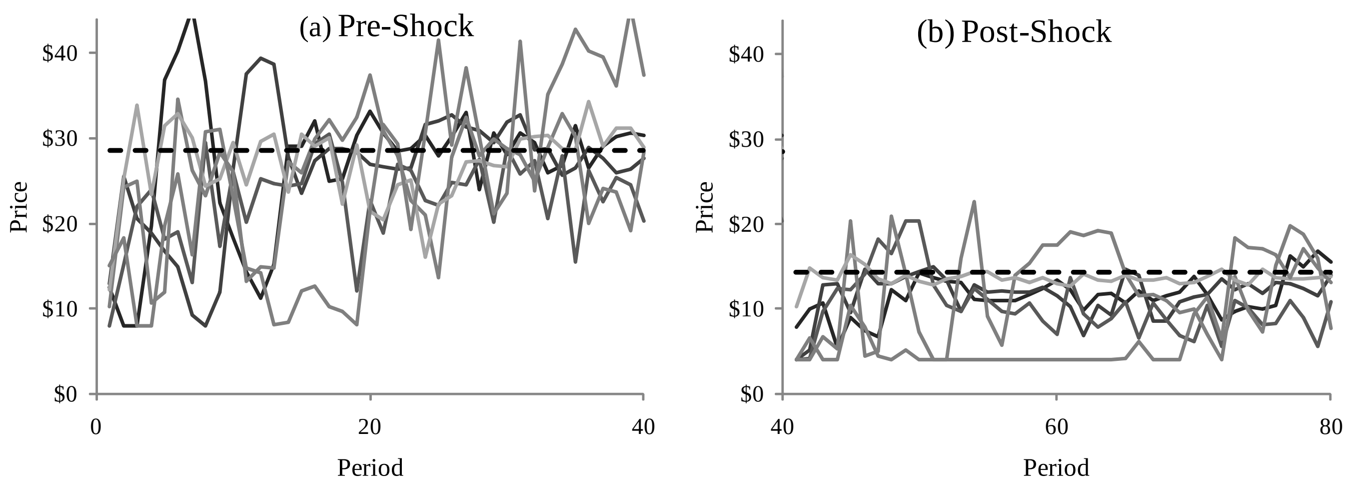

Figure 2. Mean Transaction Prices, C*L* Treatment.

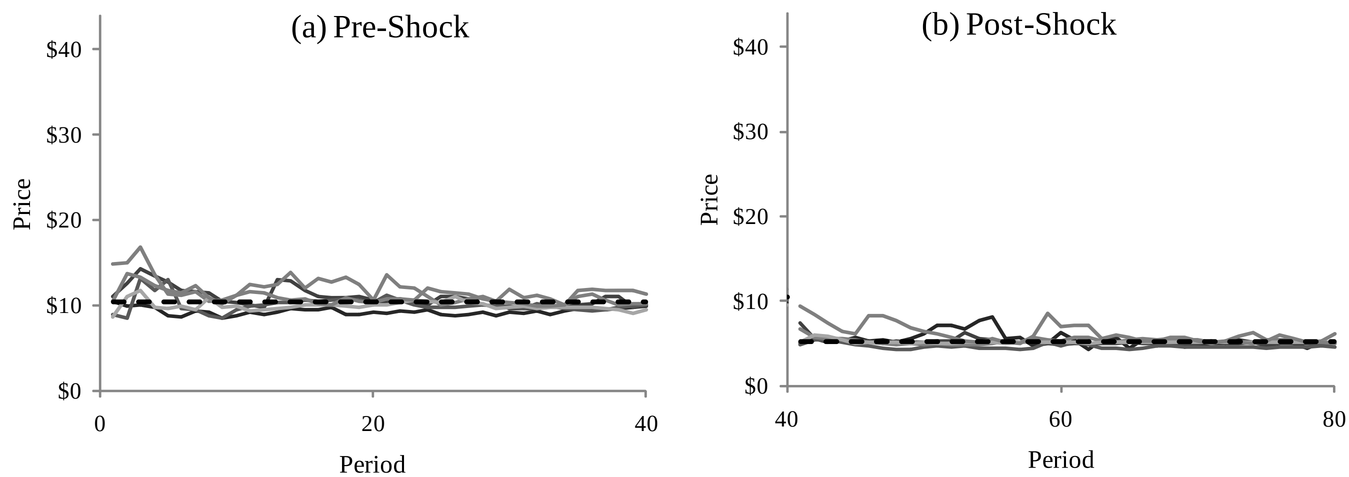

Figure 3. Mean Transaction Prices, *BH* Treatment.

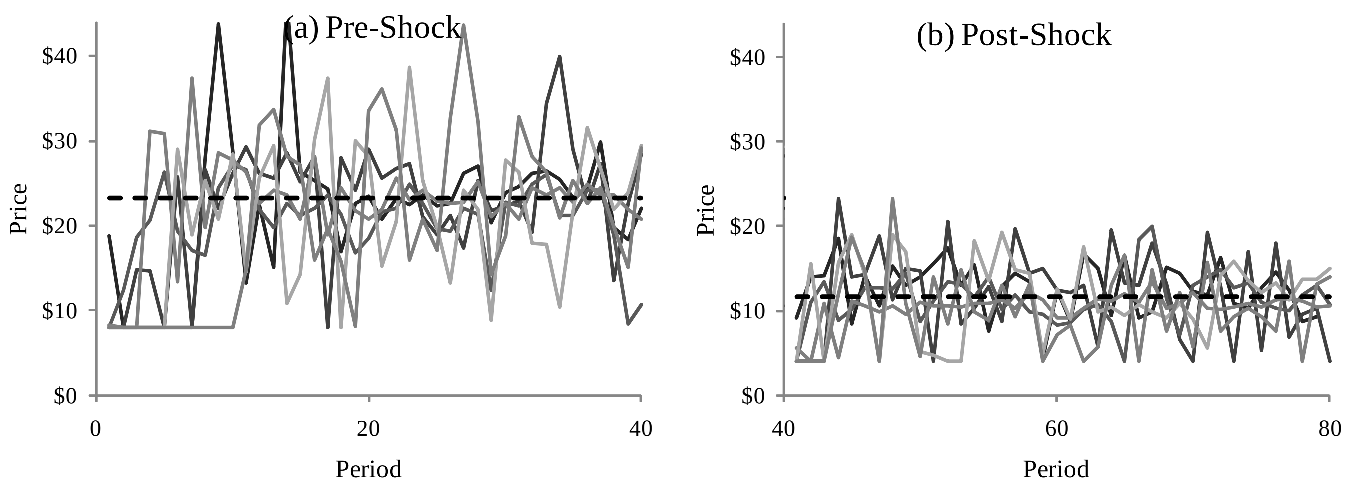

Figure 4. Mean Transaction Prices, *CH* Treatment.

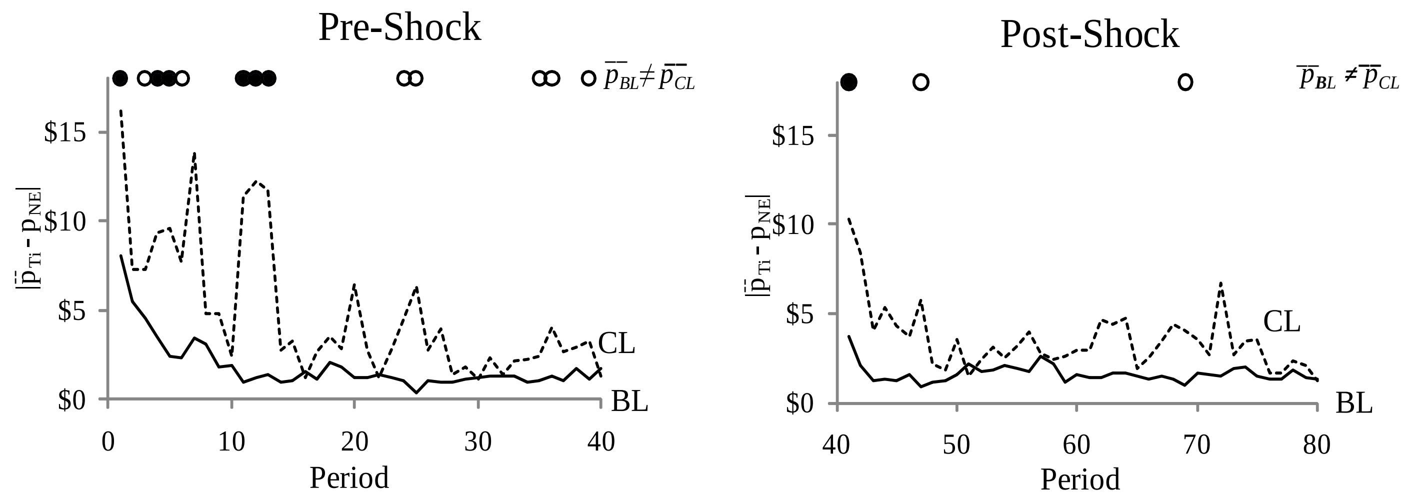

Figure 5. Absolute Median Price Deviations, *BL* and *CL*. *Key*: Circles indicate periods where the null hypothesis that median price deviations are equal in the two treatments is rejected. '●' p<.05, '○' p<.10. (Two-tailed Mann-Whitney tests).

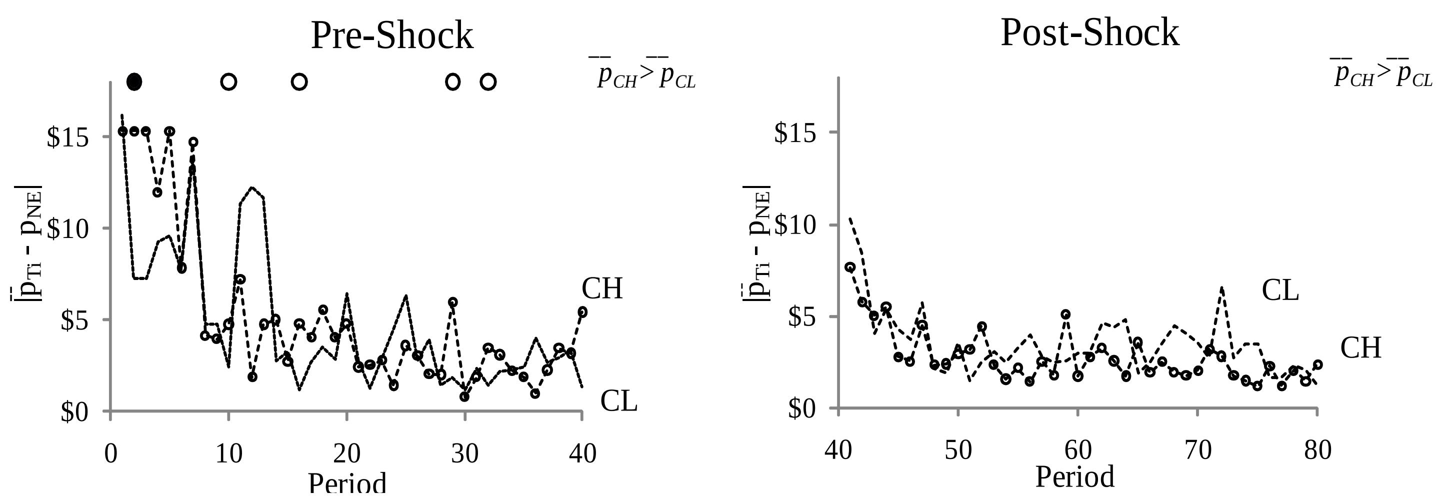

Figure 6. Absolute Median Price Deviations, *CH* and *CL*. *Key*: Circles indicate periods where the null hypothesis that median price deviations are equal in the two treatments is rejected. '●' p<.05, '○' p<.10. (One-tailed Mann-Whitney tests).

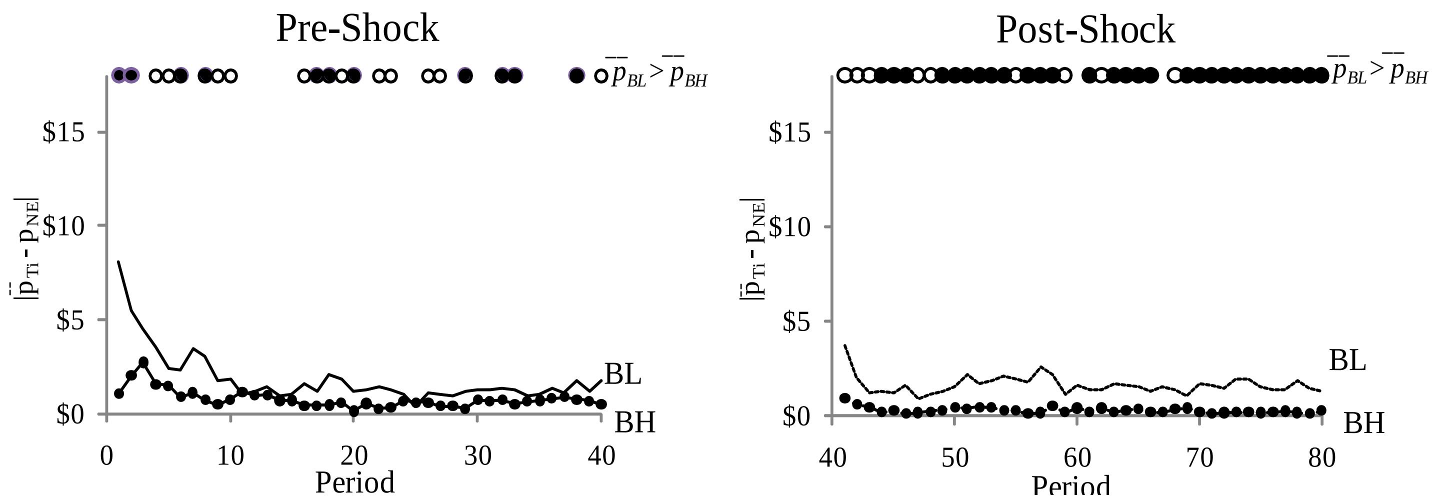

Figure 7. Absolute Median Price Deviations, *BH* and *BL*. *Key*: Circles indicate periods where the null hypothesis that median price deviations are equal in the two treatments is rejected. '●' p<.05, '○' p<.10. (One-tailed Mann-Whitney tests).

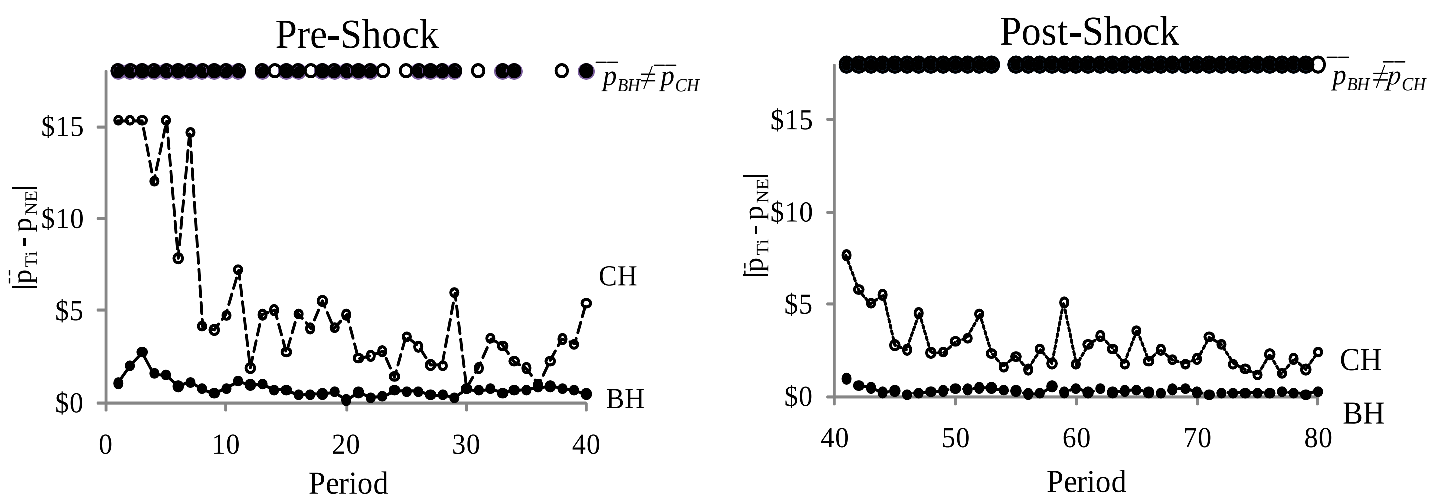

Figure 8. Absolute Median Price Deviations, *BH* and *CH*. *Key*: Circles indicate periods where the null hypothesis that median price deviations are equal in the two treatments is rejected. '●' p<.05, '○' p<.10. (Two-tailed Mann-Whitney tests).

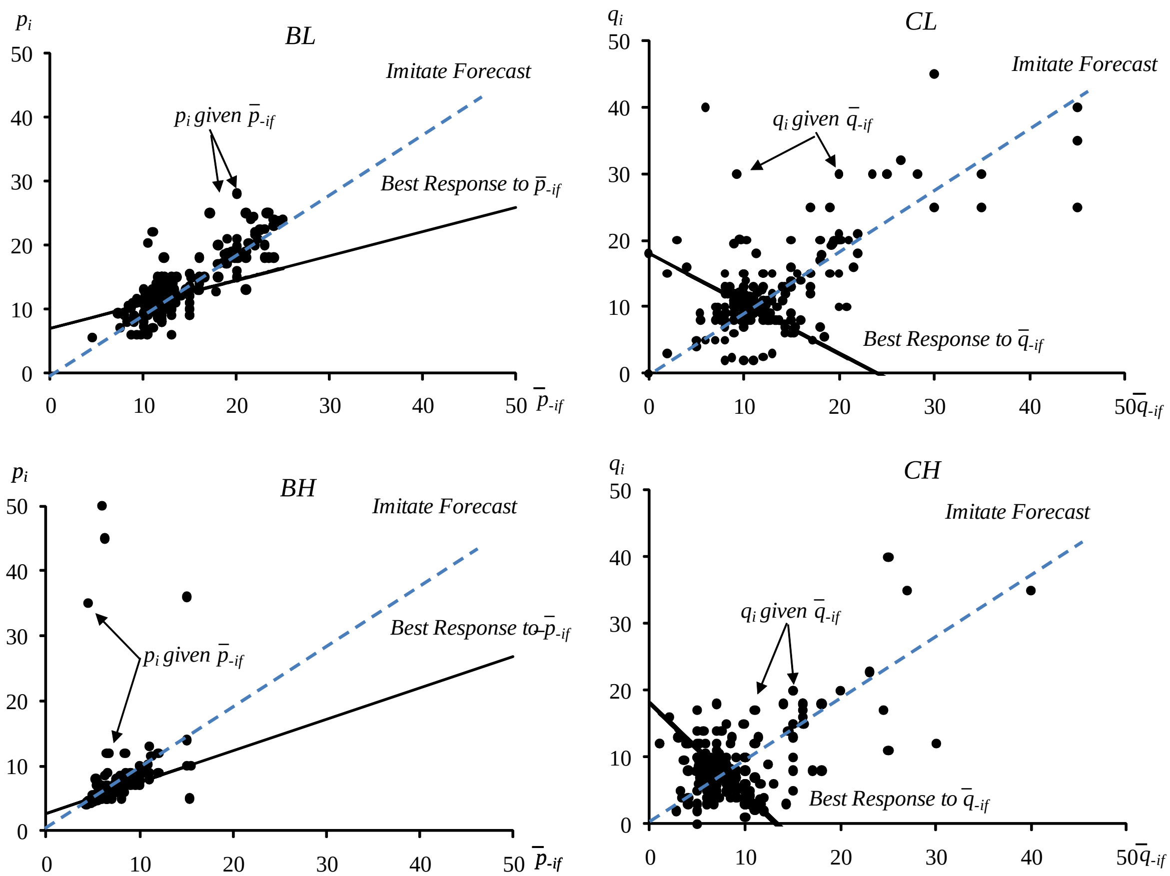

Figure 9. Action choices and best responses to forecasts, periods 41-50.

Table A1. Percentage of Action Choices within a Neighborhood of the Nash Equilibrium, Periods 36-40

(1) Mean	(2) Treatment	(3) *BH*	(4) *BL*	(5) *CH*	(6) *CL*
		Pre-Shock			
5% Neighborhood					
89%	*BH*	--	0.02*	0.00*	0.00*
45%	*BL*		--	0.30	0.15
30%	*CH*			--	0.47
24%	*CL*				--
10% Neighborhood					
95%	*BH*	--	0.05*	0.00*	0.00*
80%	*BL*		--	0.04*	0.01*
47%	*CH*			--	0.33
37%	*CL*				--
		Post-Shock			
5% Neighborhood					
94%	*BH*	--	0.00*	0.00*	0.00*
41%	*BL*		--	0.52	0.17
30%	*CH*			--	0.19
17%	*CL*				--
10% Neighborhood					
93%	*BH*	--	0.15	0.00*	0.00*
54%	*BL*		--	0.34	0.29
27%	*CH*			--	0.81
28%	*CL*				--

Key: In each treatment we define a 'neighborhood' as deviations from the Nash equilibrium prediction that are less than or equal to either 5% or 10% of the Walrasian to Joint Maximizing Range. Entries in columns (4) to (6) report *p* values for a test of the null hypothesis that the row and column treatments do not differ. '*'s highlight instances where the treatments at $p<.05$ using a two tailed Mann-Whitney test.

Table A2. Absolute and Relative Proximity to Action Anchors

	Absolute Proximity			Relative Proximity		
	Periods 2-20					
	(1) Optimization	(2) Herding	(3) Inertia	(4) Optimization	(5) Herding	(6) Inertia
BH	78%	64%	62%	43%	24%	33%
BL	46%	54%	55%	31%	30%	39%
CH	18%	17%	26%	33%	31%	36%
CL	20%	25%	28%	30%	33%	38%
Overall				34%	29%	36%
	Periods 21-40					
BH	90%	83%	83%	39%	23%	38%
BL	58%	65%	75%	25%	28%	47%
CH	34%	31%	40%	40%	23%	37%
CL	33%	30%	37%	32%	29%	39%
Overall				34%	26%	40%

Key: 'Absolute Proximity' is the percentage of action choices that are within 5% of the Walrasian to Joint Maximizing range of the anchor. ''Relative proximity' is the percentage of action choices that are relatively closer to one anchor than to the others. 'Optimization.' is a best reply to an agent's forecast of others' actions, 'Herding' is an agent's forecast of others' actions and 'inertia' is an agent's previous period action.

Table A3. Signaling Activity

(1) Treatment	(2) Market						(3) Overall
	i	*ii*	*iii*	*iv*	*v*	*vi*	
			Spikes / Surges*				
			Initial Sequence				
BH	6/ 0	7/ 0	9/ 0	4/ 0	7/ 0	4/ 0	37/ 0
BL	1/ 0	0/ 0	6/ 14	**2/ 26**	4/ 12	2/ 21	3/ 73
CH	0/ 11	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 11
CL	0/ 0	0/ 11	0/ 0	0/ 11	0/ 11	0/ 0	0/ 33
			Post Shock Sequence				
BH	10/ 0	11/ 0	11/ 0	5/ 0	15/ 0	5/ 0	52/ 0
BL	**0/ 33**	0/ 0	2/ 0	0/ 13	**5/ 11**	**3/ 31**	10/ 88
CH	0/ 13	1/ 0	1/ 0	2/ 0	0/ 0	0/ 0	4/ 13
CL	0/ 0	0/ 0	3/ 0	2/ 0	0/ 0	0/ 0	5/ 0

* Notes: 'Spikes' are quantity postings of zero, or a price postings that yield sales of zero. 'Surges' are consecutive periods of quantity postings below, or price postings above the best reply by a margin sufficient to miss the forecasting prize (10 minimum). Bolded entries highlight instances where prices deviated markedly from Nash predictions in the *BL* treatment.

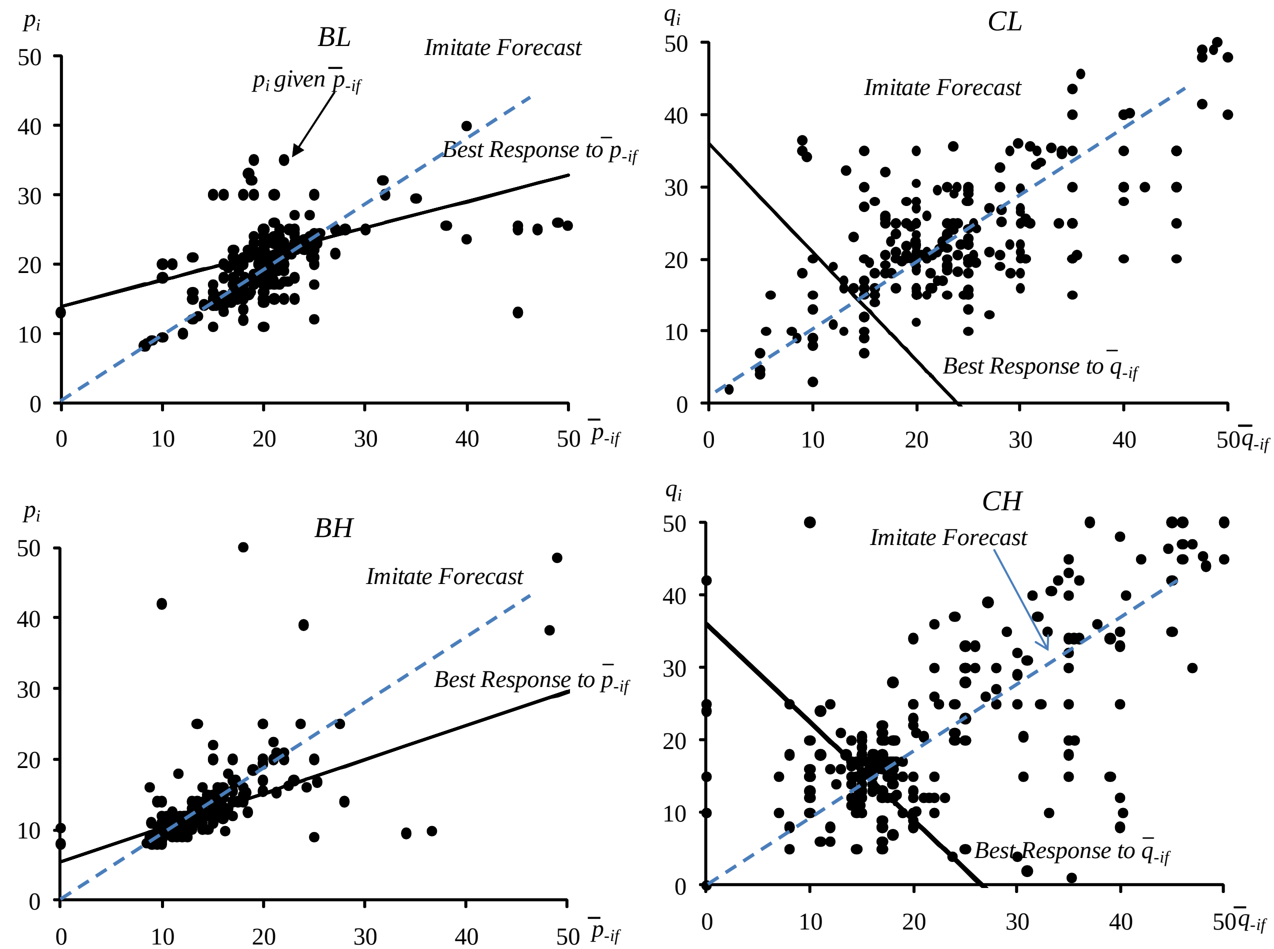

Figure A1. Seller responses to forecasts, periods 1-10.